

Chapter 2

Multivariate Statistical Analysis for Seismotectonic Provinces Using Earthquake, Active Fault, and Crustal Structure Datasets

Takashi Kumamoto, Masataka Tsukada, and Masatoshi Fujita

Abstract Seismotectonic zonation for seismic hazard assessment of background faults and earthquakes by the Headquarters for Earthquake Research Promotion (HERP [1]) is based on the results of the seismotectonic boundaries of Kakimi et al. [2]. However, several unsolved problems, such as map scale, remain in this approach for better prediction of the magnitude and frequency of blind earthquakes. The aim of this study was to construct a new quantitative and objective seismotectonic province map for the main islands of Japan (Honshu) for rational earthquake size estimation of blind faults and earthquakes. The resolution of the map was set as the second-order map grid of ca. 10 by 10 km of the Geographic Survey of Japan. Then, the parameters of (1) observed seismicity, (2) distribution of active faults converted to earthquake moment release rate, (3) width of the seismogenic layer, and (4) Bouguer gravity anomaly were assigned independently to each grid for principal component analysis. The first principal component of the principal analysis in this study represents the degree of tectonic activity for both the north-eastern and southwestern Honshu islands. The resulting principal component scores were then applied to a cluster analysis to conduct quantitative classifications, and the result provided three and nine seismotectonic provinces in the northeastern and southwestern Honshu islands, respectively.

Keywords Seismotectonic province map • Principal component analysis • Cluster analysis

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2.1 Introduction

Two types of intraplate earthquake are independently considered when constructing National Seismic Hazard Maps for Japan. One is earthquakes with a specific active fault, such as the 1995 Hyogo-ken-nambu (Kobe) earthquake of M_{JMA} 7.3 (magnitude of the Japan Meteorological Agency), for which the results of tectonic land-form analysis and trenching surveys are used for evaluation. The other is background earthquakes, such as the 2000 Tottori-ken Seibu earthquake of M_{JMA} 7.3 and the 2008 Iwate-Miyagi Nairiku Earthquake of M_{JMA} 7.2, for which no surface observation data are available for magnitude and frequency evaluation (HERP [1]). Instead, both the earthquake statistics model of the Gutenberg-Richter relationship for magnitude and frequency estimation and the seismotectonic province map for counting observed moderate to small-sized earthquakes for the earthquake statistics are needed for hazard assessment. The HERP (2009) referred to the tectonic province map of Kakimi et al. [2]. This map was constructed by examining the density of active faults and earthquakes, focal mechanism of earthquakes, and the general tectonic setting. The tectonic boundaries of this map are shown in Fig. 2.1. Then, the magnitude for the maximum-size background earthquake was determined by referring to the historical earthquake records, and the frequency of this earthquake was calculated from the Gutenberg-Richter relationship and instrumentally observed seismicity. However, the following unsolved problems remain for application of the tectonic province map to the National Seismic Hazard Maps for Japan:

1. The main purpose of the tectonic province map of Kakimi et al. [2] is to evaluate the maximum-size earthquake, including an earthquake with a specific fault.
2. The scale of the map is 1:2,000,000, which is too small to discuss boundary locations.
3. The regulation for setting boundaries was based mainly on the subjective analysis of experienced researchers under the reference datasets mentioned above.

Therefore, the aim of this study is to construct a seismotectonic province map by quantitative and objective methods. For this purpose, we adopted the following four datasets: observed seismicity, the distribution of active faults, the lower limit of the seismogenic layer, and the Bouguer gravity anomaly.

The statistical methods adopted in this research for the multivariate analysis are principal component analysis and cluster analysis. The spatial resolution for the analysis was set as the second-order map grid of ca. 10 by 10 km of the Geographic Survey of Japan. Then, the four datasets were compiled for each grid, and the principal component loadings were calculated for the cluster analysis. Finally, the boundaries of the tectonic province map were depicted by referring to the result of the cluster analysis.

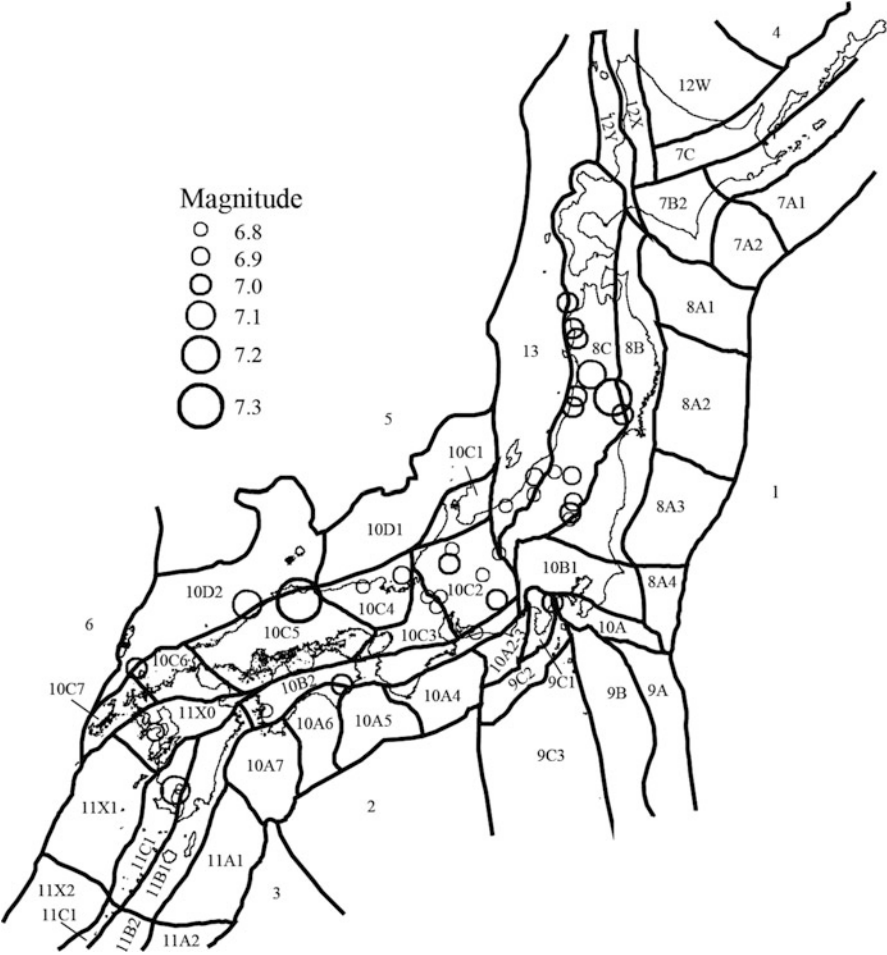


Fig. 2.1 Boundaries among seismotectonic provinces after Kakimi et al. [2]. Circles show intraplate blind earthquakes during 1926–2011

2.2 Data and Method

To construct the seismotectonic province map by the principal component analysis, we parameterized the observed seismicity, distribution of active faults, lower limit of the seismogenic layer, and Bouguer gravity anomaly as explained below.

2.2.1 Observed Seismicity (Fig. 2.2a)

For the instrumentally observed seismicity data, we extracted earthquakes of magnitude 4.0 or larger with depths of 20 km or shallower during 1926–1995 from the Japan Meteorological Agency’s integrated hypocenter database. Next, aftershocks due to large earthquakes of magnitude 6.0 or larger in the same period were excluded by the method of the Public Works Research Institute [3]. Then, the magnitude M_{JMA} of each earthquake in a grid was converted to seismic moment M_0 [dyne-cm] by the Eq. (2.1) of Takemura [4].

$$\text{Log}M_0 = 1.2 M_{\text{JMA}} + 17.7 \quad (2.1)$$

Finally, the logarithmic summation of the seismic moments of the earthquakes per year in the grid was calculated as a parameter of the observed seismicity (Fig. 2.3a).

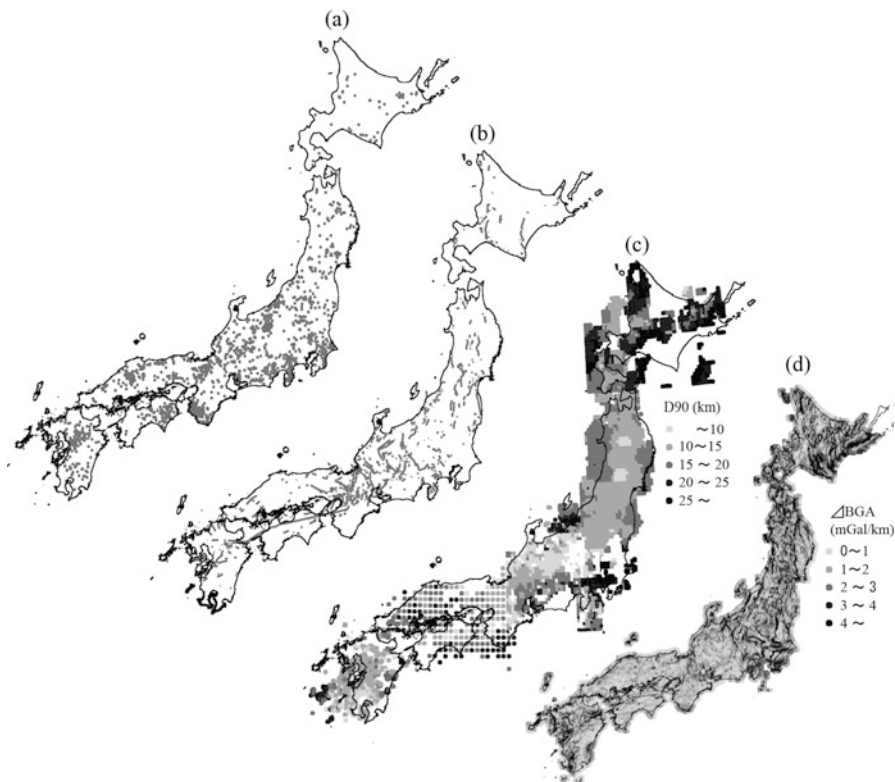


Fig. 2.2 Original parameters for the principal component analysis: (a) seismicity, (b) distribution of active faults, (c) lower limit depth of the seismogenic layer, and (d) inclination of Bouguer gravity anomaly

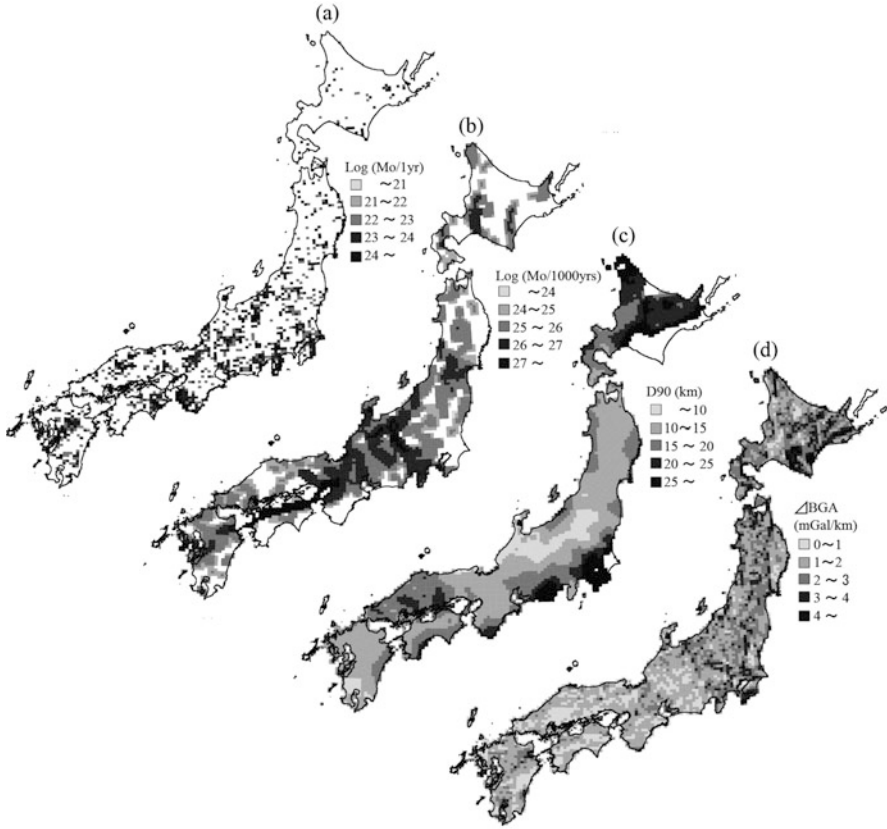


Fig. 2.3 Parameters assigned to the second-order map grid (scale 1:25,000) for the principal component analysis: (a) logarithmic seismic moment release rate per year, (b) logarithmic seismic moment release rate per 1k year, (c) weighted average lower limit depth of the seismogenic layer, and (d) averaged inclination of the Bouguer gravity anomaly

2.2.2 Distribution of Active Faults (Fig. 2.2b)

In order to include the long-term averaged seismicity data with thousands to tens of thousands of years, that is, almost identical to the average recurrence period of active faults in Japan, the distribution map of active faults was used in the principal component analysis. The seismogenic fault distribution database of Okino and Kumamoto [5], which is a recompilation of the Digital Active Fault Map of Japan (Nakata and Imaizumu, eds., [6]), was used. The length of each seismogenic fault L (km) was converted to M_{JMA} by Mastuda's Eq. (2.2) [7] and then reconverted to seismic moment M_o by equation (1).

$$\text{LogL} = 0.6M_{\text{JMA}} - 2.9 \quad (2.2)$$

Next, the seismic moment M_0 of each seismogenic fault was divided by the averaged recurrence interval derived from trenching surveys or empirical equations, and the seismic moment release rate per 1000 yr was calculated.

If the seismic moment release rate of a seismogenic fault is assigned to grids that are cut through by the seismogenic fault, the contrast between a grid with the seismogenic fault and a neighboring grid without the seismogenic fault becomes too large. A trial test with such contrast clarified that severe bias results in the principal component analysis. Therefore, the seismic moment release rate of such a grid was redistributed to the neighboring eight grids by using the Gaussian weighting function. This procedure corresponds to the consideration of subsidiary faults around the main traces of a seismogenic fault, which is omitted in the seismogenic fault distribution database (Okino and Kumamoto [5]). Finally, the logarithmic summation of seismic moments of earthquakes per 1000 yr in the grid was calculated for a parameter of the distribution of active faults (Fig. 2.3b).

2.2.3 Lower Limit of the Seismogenic Layer (Fig. 2.2c)

As the first order subsurface structural parameter, the lower limit of the seismogenic layer D90 was adopted in this study. The D90 shows the 90 % depth among instrumentally observed seismicity in a 0.025–0.2-degree grid (Seismotectonics Research Group ed. [8]). This lower limit of the seismogenic layer data relates to the seismogenic fault width and shows locality in Japan. Interpolation with the weight of the reciprocal of a distance to a grid was applied to the D90 data, and the parameter for the principal component analysis was created (Fig. 2.3c).

2.2.4 Bouguer Gravity Anomaly (Fig. 2.2d)

Bouguer gravity anomaly data are corrected to indicate subsurface density structure, and many reports show that the specific large inclination of the Bouguer gravity anomaly corresponds to the distribution of active faults (e.g., Hagiwara ed. [9]). Thus, the data of the assumed density of 2.67 g/cm^3 with 1 km resolution from the Gravity CD-ROM of Japan Ver.2 (Geological Survey of Japan [10]) were adopted in this study for the second subsurface structural parameter. The average inclination in a grid was calculated for the principal component analysis (Fig. 2.3d).

Because the unit of each parameter was different, the correlation matrix method was used in the principal component analysis. As a result, principal component loadings, eigenvalues, coefficients of determination, cumulative coefficients of determination, and principal component scores were calculated for four parameters.

2.3 Result and Discussion

Figure 2.4 shows the first, second, third, and fourth principal component loadings for the four parameters of observed seismicity, distribution of active faults, lower limit of the seismogenic layer, and Bouguer gravity anomaly in (a) the northeastern Honshu, (b) southwestern Honshu, (c) Kyushu, (d) Hokkaido, and (e) Kanto districts resulting from the principal component analysis.

The first principal component loadings (F1) in Fig. 2.4a of northeastern Honshu showing a 34 % proportion indicate that the observed seismicity, distribution of active faults, and Bouguer gravity anomaly parameters have positive values and that the lower limit of the seismogenic layer has a negative value. This result means that the short-term observed seismicity matches well the estimated long-term

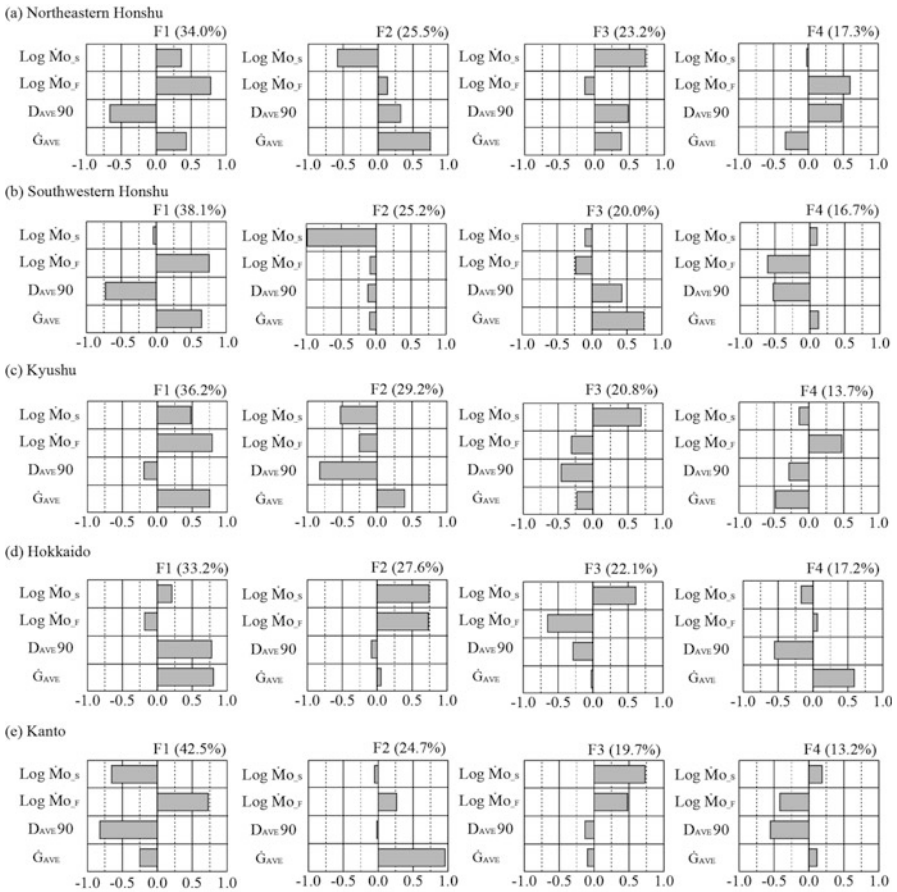


Fig. 2.4 The first to fourth principal component loadings for seismicity, active faults, lower limit depth of the seismogenic layer, and inclination of the Bouguer gravity anomaly of each region

averaged seismicity from active faults. In addition, those areas where the density of the observed seismicity and distribution of active faults are both high show a relatively thin seismogenic layer and complex subsurface structure deduced from the Bouguer gravity anomaly. Thus, we consider that the first principal component might indicate the degree of tectonic activity.

The results of the relations between the principal component loadings and four observed parameters of (b) southwestern Honshu and (c) Kyushu in Fig. 2.4 show a similar tendency. Thus, we expect that the spatial distribution of the first principal component loading relates to the seismotectonic provinces and adopted it as a parameter for the following cluster analysis. However, to the contrary, the first principal component loading (F1) in Fig. 2.4d of Hokkaido showing a 33 % proportion indicates that the lower limit of the seismogenic layer and the Bouguer gravity anomaly parameters are large positive values and that the remaining parameters are relatively small. Additionally, the first principal component loadings (F1) in Fig. 2.4e of Kanto indicate a different tendency from the other districts, showing that the first principal component loadings of the observed seismicity and Bouguer gravity anomaly parameters are largely negative. The reason for the different results for the Hokkaido and Kanto districts might relate to the distance between the district and plate boundary axis. The closer distance of the Hokkaido and Kanto districts results in complexity of the deep part of the tectonic structure, such as the depth and the shape of the subducting oceanic plate and the related seismicity and gravity anomaly.

Hereafter, cluster analysis is applied to the first principal component scores of northeastern Honshu and southwestern Honshu, respectively, from the viewpoint of the tectonic meaning of intraplate shallow earthquakes and active faults as judged from the principal component loading results (Fig. 2.4). The statistical distances among grids in each district were measured by the group average method, and clusters were calculated in similarity order. The number of clusters is after that of Kakimi et al. [2], and four and six were set for northeastern Honshu and southwestern Honshu, respectively (Fig. 2.5). The result shows that each cluster in both northeastern and southwestern Honshu distributes with strong spatial relation, although no parameter regarding contiguity was involved in the principal component analysis. Thus, the similarity of the first principal component score based on the objective index of statistical distance is considered to have usefulness for considering the spatial correlation of tectonic provinces.

Then, the tectonic province boundaries were set at the cluster boundaries between areas of clusters with the same category, as shown in Fig. 2.6a for northeastern Honshu and Fig. 2.6b for southwestern Honshu. The exception was the case of isolated cluster patches consisting of 10 or fewer grids, which were subjectively determined to be ignored or incorporated into a neighboring cluster by the shape and size of each patch. The following describes the distinctive features of our results (Fig. 2.6) and the tectonic province map of Kakimi et al. [2] (Fig. 2.1).

Northeastern Honshu was divided into two large seismotectonic provinces by Kakimi et al. [2]. This boundary is located at the eastern foot of the Ou-Backbone Mountain Range and partly overlaps with west-dipping reverse fault systems, such

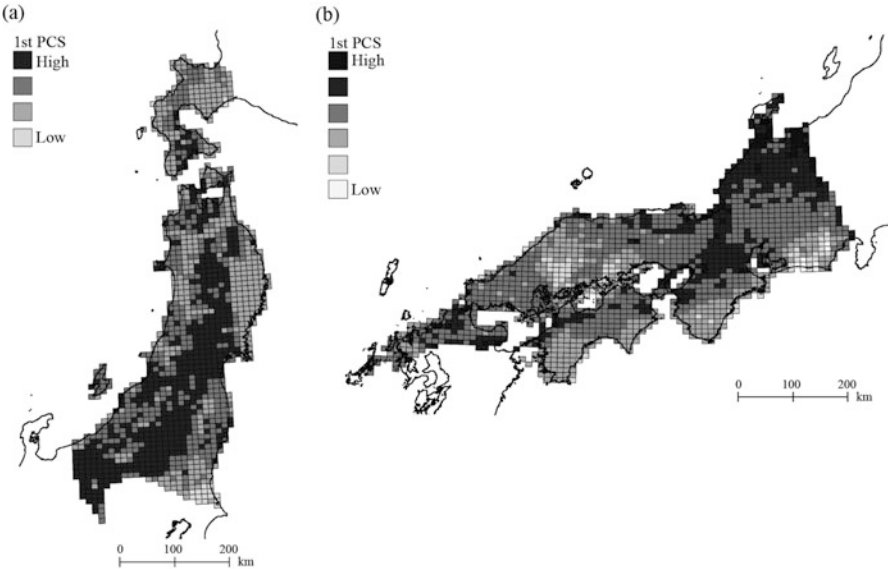


Fig. 2.5 Result of the cluster analysis using the first principal component loadings. Four and six clusters are shown for northeastern and southwestern Honshu, respectively

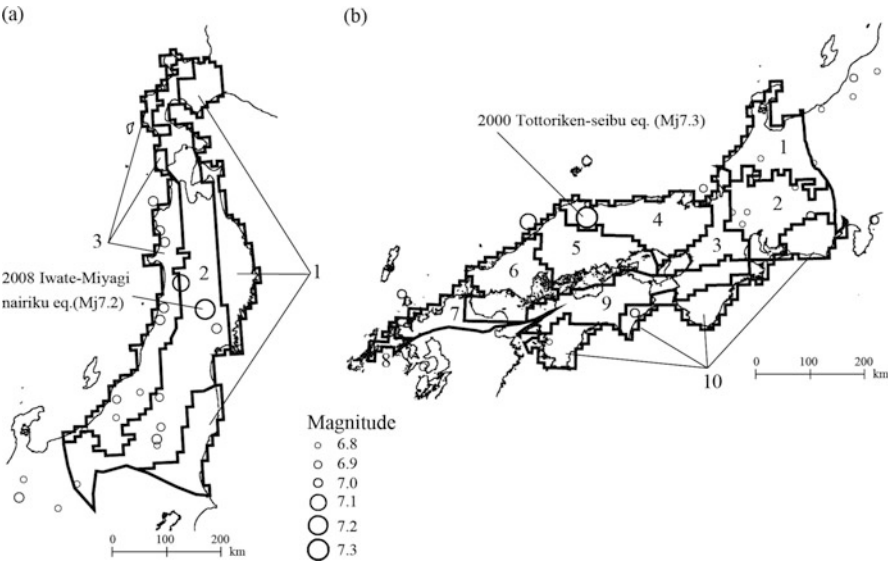


Fig. 2.6 Boundaries among the seismotectonic provinces defined in this study: (a) northeastern Honshu island with three provinces and (b) southwestern Honshu island with nine provinces

as the Kitakami lowland west boundary fault system and the Fukushima basin west boundary fault system. To the contrary, our result (Fig. 2.6a) shows that northeastern Honshu is divided into three large provinces. The eastern boundary is located 10–50 km eastward of the eastern foot of the Ou-Backbone Mountain Range, and the western boundary is located 10–50 km westward of the western foot of the Ou-Backbone Mountain Range, where the Yokote basin east boundary fault system and other east-dipping reverse fault systems are identified. Therefore, the two parallel boundaries in this study involve the Ou-Backbone Mountain Range and separate from both outer provinces with relatively low seismicity. This result is consistent with the idea that the Ou-Backbone Mountain Range was uplifted by the conjugate reverse fault system beneath the mountain ranges. From the viewpoint of our result, the background of the 2008 Iwate-Miyagi Nairiku Earthquake is then located in a province with high density of seismicity and active faults.

In this study, southwestern Honshu was divided into nine seismotectonic provinces (Fig. 2.6b), and the number of provinces is the same as that of Kakimi et al. [2]. There are three major differences in southwestern Honshu between Fig. 2.6b and Fig. 2.1: First, in Kakimi et al. [2], the Median Tectonic Line (MTL), the longest and one of the most active fault systems in Japan, is excluded from the province as an exception of the specific fault and overlaps the boundary between the outer and inner zones of southwestern Honshu. However, our objective calculation results in a province involving the MTL without exceptional consideration, influenced mainly by the density contrast of the active fault distribution (No. 9 of Fig. 2.6b). Second, in Kakimi et al. [2], the seismotectonic boundary between the Kinki district with a high density of seismicity and active faults and the Chugoku district with a low density of each is located at the Yamazaki fault system and its extensions. This boundary excludes the background earthquake of the 2000 Tottori-ken Seibu Earthquake from the province with a high density of seismicity and active faults. To the contrary, our result (Fig. 2.6b) shows that the boundary is located westward by 20–30 km in the southern section and 50–80 km in the northern section. Thus, both the source fault of the 2000 Tottori-ken Seibu Earthquake and the Shimane nuclear power plant site in the Shimane Peninsula are included in the same seismotectonic province of the Kinki district where the high density of seismicity and active faults are observed. Third, the Chugoku district is divided into two seismotectonic provinces corresponding to the density difference of active fault distribution (Fig. 2.3b, whereas it is one large province in the map of Kakimi et al. [2].

2.4 Future Challenges

In this study, a new quantitative and objective seismotectonic province map for improvement of background earthquake assessment was constructed by combining the four datasets of observed seismicity, distribution of active faults, lower limit of the seismogenic layer, and Bouguer gravity anomaly and the statistical methods of

principal component analysis and cluster analysis. The resulting map in Fig. 2.6 shows different tectonic province boundaries and the necessity of a different explanation regarding the 2000 Tottori-ken Seibu Earthquake and the 2008 Iwate-Miyagi Nairiku Earthquake, which represent large background earthquakes. Future improvement is still needed in regard to ways to estimate the largest magnitude and associated frequency of background earthquake in a rational and objective seismic hazard assessment, not only in each province but also at the site of a nuclear power plant.

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